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Roadmap toward a planetary sunshade for space-based solar geoengineering

Catello Leonardo Matonti [a,*], Marina Coco [a], Chantal Cappelletti [b], Bruce Chesley [c], Christer Fuglesang [d], Giuseppe Governale [a], Nishanth Pushparaj [b], Marcello Romano [e], Gunnar Tibert [d], Lisa Wilk [d]

[a] Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, Turin 10129, Italy
[b] Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom
[c] Teaching Science and Technology, Inc., Monument, CO, 719-494-9739, USA
[d] Division of Aerospace, Moveability and Naval Architecture, KTH Royal Institute of Technology, Teknikringen 8, SE-100 44, Stockholm, Sweden
[e] Chair of Astrodynamics, Technical University of Munich, Willy-Messerschmitt-Str. 11, Munich 82024, Germany

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Abstract

Climate change mitigation may require transformative strategies beyond emission reduction. This paper introduces a technology roadmap for developing a Planetary Sunshade System: a space-based solar geoengineering concept designed for reversible Solar Radiation Management. The proposed roadmap is a structured, multi-phase plan from early technology demonstrations to full deployment at the Sun–Earth/Moon Center of Mass photo-gravitational Lagrange point. The roadmap addresses critical aspects such as solar-sail design, in-space assembly, swarm logistics, and launch infrastructure, while outlining milestones for initial operations by 2040 and full capability by 2080. By integrating technological, logistical, and programmatic considerations, this roadmap serves as a framework for assessing feasibility and guiding international collaboration on space-based climate interventions.

Keywords: Planetary sunshade; Space-based geoengineering; Climate change mitigation; Roadmap; Technology development; In-space assembly

1. Introduction

Climate change is one of the most pressing challenges of our time, driven primarily by the increasing concentration of greenhouse gases in the atmosphere (Hardy, 2003). The rising levels of greenhouse gases in our atmosphere, primarily caused by human activities such as burning fossil fuels, deforestation, and industrial processes, have resulted in significant global temperature increases (Lee et al., 2023). Addressing climate change necessitates the exploration of various mitigation strategies, including cutting greenhouse gas emissions and implementing adaptation measures to manage unavoidable impacts (Crowley, 2000). However, these efforts alone may not be sufficient to avert the most severe outcomes of global warming. This realization has led the scientific community to explore more innovative and potentially transformative approaches, such as solar geoengineering (Irvine et al., 2016). This paper offers a valuable and original contribution to this emerging field, by introducing a comprehensive roadmap

* Corresponding author.
E-mail addresses: catello.matonti@polito.it (C.L. Matonti), marina.coco@polito.it (M. Coco), chantal.cappelletti@nottingham.ac.uk (C. Cappelletti), bruce.c.chesley@gmail.com (B. Chesley), cfug@kth.se (C. Fuglesang), giuseppe.governale@polito.it (G. Governale), nishanth.Pushparaj@nottingham.ac.uk (N. Pushparaj), marcello.romano@tum.de (M. Romano), tibert@kth.se (G. Tibert), lwilk@kth.se (L. Wilk).

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for the development of a Planetary Sunshade System (PSS). It combines solid scientific grounding with a visionary multi-phase strategy providing a reference for future research and policy discussions. Developing a PSS is a substantial technological and logistical challenge, requiring advances in space engineering, international cooperation, and environmental assessment, including the climate change impact. The roadmap presented here considers a step-by-step high-level plan of technology development, mission planning, launch preparation, international cooperation, highlighting the multi-phase development strategy from initial design to final deployment. The roadmap phases for production and deployment are outlined in chronological order. System-level considerations such as spacecraft mass, dimensions, sail area, and total number of solar-sail spacecraft are discussed, together with logistical aspects including in-space assembly of the fully deployed system. Launch preparation is also examined, encompassing heavy launcher design, facilities, production and launch sites. The technical analysis is grounded in established celestial mechanics, ensuring that the proposed architecture is evaluated within a rigorous dynamical framework. The proposed roadmap provides not only a starting point for the design and development of the PSS but also a critical tool for evaluating the feasibility of direct climate action from space. Through this paper, we aim to establish the groundwork for a future PSS endeavour, evaluating the feasibility and potential benefits of this innovative climate intervention, thus contributing to the broader discussion on effective and sustainable climate action. The paper is organized as follows: Section 2 presents an overview on geoengineering and sunshades. In Section 3 the Roadmap is presented. Section 4 discusses the risks and cost associated with the PSS. Section 5 highlights political challenges, while Section 6 summarizes the paper and its main contributions.

2. The sunshade programme

2.1. Geoengineering

If global temperatures threaten to exceed acceptable limits, geoengineering might become a necessary solution for global welfare (Cho, 2024). Geoengineering encompasses two main categories: Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR).

CDR focuses on reducing atmospheric CO_2 through methods such as afforestation, Bioenergy with Carbon Capture and Storage (BECCS), and Direct Air Capture (DAC) (Smith et al., 2016; Fuss et al., 2014). While DAC is theoretically ideal due to its direct approach, it is energy-intensive and must rely on fossil-free energy sources, making it less feasible in the near future (Cho, 2024).

SRM involves two primary techniques. The first aims to reflect a small percentage of the Sun's energy back into space using methods like Stratospheric Aerosol Injection (SAI) or marine cloud brightening (United Nations Environment Programme, 2023). SAI, which involves injecting aerosols into the stratosphere to reflect sunlight, is likely the less expensive method in the short term. However, it requires continuous replenishment for a decade to century long periods since aerosols remain aloft for a much shorter period compared to the centuries-long presence of CO_2 in the atmosphere (Buis, 2019). Furthermore, the potential side effects of SAI, such as changes in weather patterns and impacts on the ozone layer, also pose significant risks.

The second SRM method involves reducing solar radiation with materials placed in space and while likely more expensive, it could potentially have fewer side effects, and top-level comparisons w.r.t. atmospheric strategies have been detailed (Romano et al., 2023). Hereafter, when we talk about solar radiation reduction, the shade is referred to the electromagnetic part of solar radiation. This geoengineering solution bridges the domains of climate mitigation and space engineering, requiring a specific architectural framework (Chesley et al., 2023) but also critical examination of the perception, promise and relevance of this strategy. Our proposal is to deploy a *Planetary Sunshade System*, a set of membranes positioned between the Sun and Earth. These membranes could be controlled from Earth and quickly rotated to cease the shading effect if necessary. The optimal position for the sunshade from several aspects is beyond classic Lagrange equilibrium point L_1 in the Sun–Earth–Moon system, ca 1.5 million km away from Earth (McInnes, 2010). In principle, one could consider the membranes to be in orbit around Earth (He and Zheng, 2017), however, this is less efficient (Windh, 2020) because shading would occur less than half the time and it would add to the problem of space crowding.

2.2. Background, requirements and objectives

The PSS is a space-based reversible solar geoengineering infrastructure proposed to reduce the oncoming solar radiance by positioning the system between the Sun and Earth. Fig. 1 shows how a PSS assembled to one unit would look like in front of the Sun from Earth, compared to how Venus looks.

In 1989 James T. Early proposed a 2000 km-wide glass shield at the Sun-Earth first Lagrange point L_1, to counteract the greenhouse effect on Earth (Early, 1989). The first (to the authors' knowledge) to propose a solution with Earth-manufactured shades, was Roger Angel in 2006 (Roger, 2006). He suggested trillions of flying small space robots, weighing 1 gram each, which would be launched with a gigantic electromagnetic gun embedded in a mountain. Generally, the main strategy consists of a swarm of solar-sail spacecraft, capable of active control, which can be either totally or partially assembled to build one or more occulting disks. The swarm astrodynamics, with the proposition of suitable families of photo-gravitational Halo orbits, has been investigated in (Matonti et al., 2023;

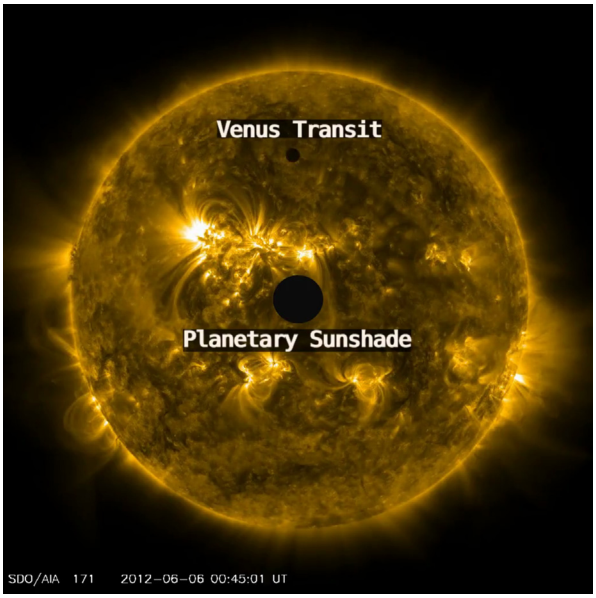

Fig. 1. Conceptual visualization of space-based climate change mitigation strategy represented by a Planetary Sunshade system, compared with a Venus transit as seen from Earth on 06/06/2012, source (Pesnell, 2012).

Matonti and Romano, 2024) while orbital transfers strategies are analyzed in (Fuglesang and de Herreros Miciano, 2021; Matonti et al., 2023).

Finally, other architectures have been proposed utilizing space resources (Jehle et al., 2020; Baum et al., 2022), including the Moon (Maheswaran, 2021). The reason for considering space resources lies on the very large cost to launch from Earth millions of tonne needed for a sufficiently large shade, or systems of smaller shades. However, recent developments in new rockets are drastically changing the space accessibility. The "rule of thumb", until about 20 years ago, used to be that the price to send one kg to space was $10,000. It has already fallen by almost an order of magnitude and is expected to fall by at least one more (Citi Global Perspectives & Solutions, 2022). It is now realistic to consider a Planetary Sunshade that is manufactured on Earth (Fuglesang and de Herreros Miciano, 2021).

With current climatological trends (Lee et al., 2023), it might be necessary to start implementing a Planetary Sunshade already in the 2040s. By then, some critical in-space manufacturing technologies may not be at a high Technological Readiness Level (TRL). Therefore, we assume that the Planetary Sunshade Roadmap will consider on-Earth production of its modules. The total size of the Planetary Sunshade would depend on the mitigation scenario chosen, such as how much cooling would be needed and shall some latitude variation be implemented. Typically, assumptions vary between 0.5% and 2% shading, much based on a study claiming that a global solar radiance reduction of about 1.7% would be needed to mitigate the effects of doubling the carbon dioxide concentration in the atmosphere (Govindasamy and Caldeira, 2000). The total area of such a system, placed in the vicinity of photo-gravitational L_1, is about 10^6 km^2. The mass would be in the order of 10^8 to 10^{12} kg, mainly depending on the optical properties of the membrane. Among the phases of the sunshade programme, the following is considered:

1. Development and manufacturing of the Sunshade (including in-space transfer capabilities). A membrane will be selected and developed. Its optical properties will drive the total mass of the whole system, together with the deployment mechanism and structure for these large areas. These can include some assembly mechanisms and capabilities.
2. Launch to space (probably to Earth orbit), which can be assumed to be the main cost driver.
3. Transfer of sunshades from Earth orbit to the final position, for example, by solar sailing or electric propulsion, or a combination thereof.
4. Station keeping, operation and coordination at the final position. These can include assembly and formation flight maneuvers.

Since there probably will be thousands or even millions of individual sunshade spacecraft, swarm control for formation flying is necessary. Optimal orbit for climate mitigation should also be implemented (Matonti et al., 2023; Matonti and Romano, 2024; Sánchez and McInnes, 2015; Oggionni et al., 2022). Among other developments, it might be necessary to add relay spacecraft outside the Sun–Earth line for communication due to massive radio noise coming from the Sun (Silverberg and Granberg, 2024). The Roadmap to a Planetary Sunshade should include the steps of how to study and optimize these phases and consider the implications and consequences. Development with tests, including in-orbit precursors, should be done as soon as possible in order to have a ready design for a whole system that could be implemented from 2040, if necessary.

2.3. Mass and position optimization

The photo-gravitational Circular Restricted Three Body Problem (CR3BP) model is employed to study the dynamics of the system. In this model, the two primary bodies are the Sun and the Earth/Moon Center of Mass (CoM), modeled as point masses with a fixed distance of 1 astronomical unit (AU) between them. Both bodies are assumed to follow circular orbits around their common CoM (Koon et al., 2000). In this work, the values of primaries' masses and orbital parameters are adopted as per NASA's Sun, Earth, Moon Fact Sheet (Williams, 2024), and these are used to non-dimensionalize the photo-gravitational CR3BP equations. In this model, a solar-sail spacecraft is influenced by the gravitational attraction of both the Sun and the Earth-Moon system, as well as the Solar Radiation Pressure (SRP). SRP is the force exerted by sunlight photons striking the surface of the spacecraft, with the direction of the force assumed to be parallel to the solar sail's surface normal vector, denoted by $\hat{n}$ (McInnes, 1999).

Let define with Δ the solar radiance reduction needed, while with $\mathcal{Q}$ the solar-sail optical properties parameter which depends on the solar-sail material, ranging from perfectly reflecting surface with $\mathcal{Q} = 1$ to $\mathcal{Q} = 0$ for total transparency. Thus, the SRP is directly proportional to $\mathcal{Q}$. Then, by defining $d_{L_1^*}$ as the distance of the photo-gravitational equilibrium point L_1^* from Earth/Moon CoM, it is possible to demonstrate that there exists an optimum distance that minimizes the total mass of the system. This optimum is independent of Δ and $\mathcal{Q}$ but the mass M has a linear dependency on those parameteres, while the area has a linear dependency too but only for Δ (McInnes, 2010). The optimal distance obtained is $d_{L_1^*} \sim 2.367 \cdot 10^6$km (with a distance from L_1 associated to pure CR3BP equal to $d_{L_1^* L_1} = 8.687 \cdot 10^5$ km).

3. Roadmap toward a planetary sunshade

Developing a comprehensive roadmap for a project as ambitious as a Planetary Sunshade requires a detailed long-term plan that addresses not only technological advancements but also financial, political, and logistical challenges. Although technological aspects are relatively well understood with no clear show-stoppers, the most significant challenges lie in overcoming financial and political obstacles. This section will primarily focus on the technological roadmap, recognizing that those other factors are critical but beyond the scope of this discussion.

The roadmap for the Planetary Sunshade should be structured around a two key milestones that must occur before its outcomes can be observed (see also Fig. 2):

Technology development by 2040 Ensuring the capability to start operations of the PSS programme and its first stages.

Full deployment by 2080 Establishing a timeline for achieving a fully operational PSS fulfilling all the programme's goals.The starting year **2040** for the deployment phase is selected based on a conservative estimate to allow sufficient time for the readiness of key launchers and solar sail technologies, completion of necessary infrastructure, and scaling up of production capacities. The year **2080** has been chosen as the target for full deployment to align with critical climate action milestones outlined in Macmartin et al. (2018), which identifies the end of the current century as the timeframe by which global temperature stabilization or reversal may be achieved, depending on the climate change mitigation strategy employed. This includes scenarios such as RCP4.5 alone, RCP4.5 with long-term CDR, and RCP4.5 with both CDR and SRM, which is the most relevant in our context. In all cases, the goal is to limit warming below 2°C or 1.5°C Paris Agreement's target. Moreover, several outcomes and objectives are beyond the scope of this programme roadmap. For example, definition of the technological and political dependencies, including the necessary agreements, and the remote sensing systems to monitor and maintain desired Earth climate outomes. These supporting remote sensing systems and climate models will be essential for optimizing the addition or subtraction of PSS elements.

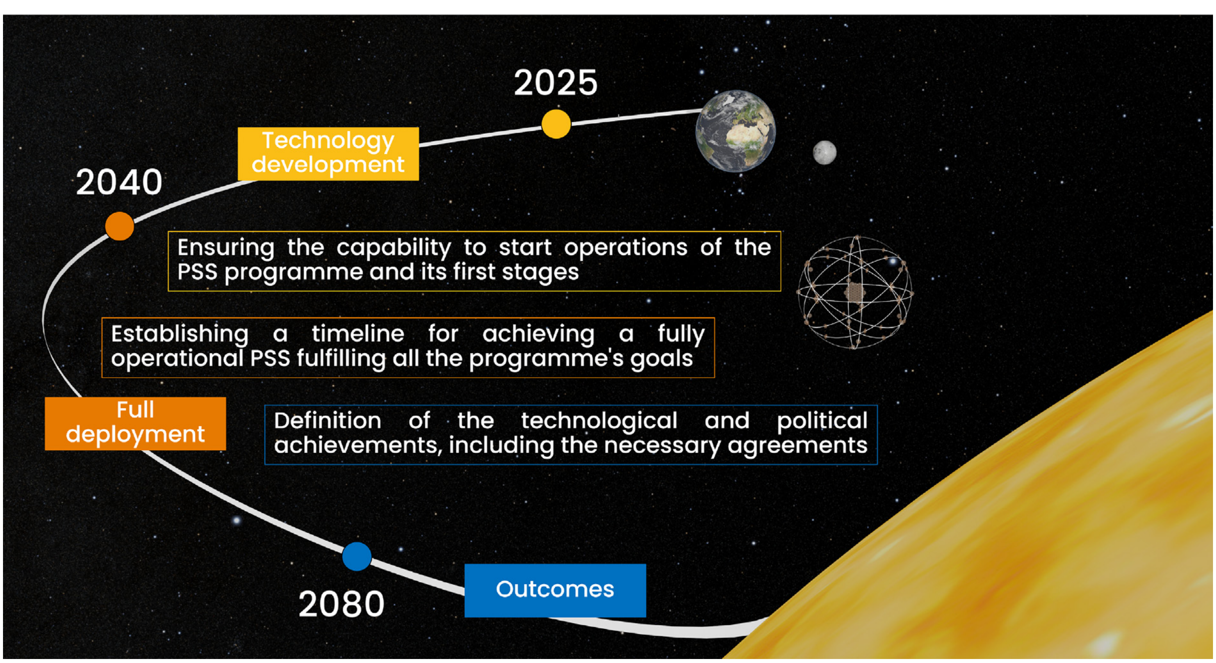

Fig. 2. Key milestones of the technology roadmap for the Planetary Sunshade programme that must occur before its outcomes can be observed.

3.1. Roadmap infographic

A preliminary technology roadmap is produced in the infographic in Fig. 3. The goal is to provide the reader with a potential roadmap structure, with no claim to provide a roadmap completed with all the necessary development steps for the sunshade programme.

As previously introduced, the roadmap timeline is divided into three main phases according to the two critical date of 2040 and 2080. In particular, in the period **2025–2040** there is a focus on early technology demonstration, operational testing, and limited deployment, specifically for in-space assembly operations. Subsequently, from **2040–2080** it is expected a development towards enhanced operational capability, while monitoring and maintain Earth climate outcomes. During the final phase, from **2080 and beyond**, there will be a full operational capability and the overall system sustainment, evolution, maintenance and replenishment, while mitigating partially the climate change effects. Moreover, in the *beyond* part of the timeline, it would be possible to define the technology transfer generated by the programme and the possible envisioned scenario for the programme itself, i.e. to maintain and sustain the system or to decommission it.

A further categorization is performed with three horizontal domains as.

Earth surface: Encompasses technology maturation, prototype production, manufacturing and the transition from low-rate to enhanced production capability for operational, replenishment and sustainment.

Lunar & Earth orbit: Includes precursor launches, in-space assembly and manufacturing technology development and a series of demonstrations, considering the dedicated processing & launch capacity.

L_1^* **orbit**: Represents the deployment location of the PSS, with precursor missions, operational prototypes, and incremental deployment of sunshade units blocks over time.

This roadmap provides an initial structured approach for the PSS programme, integrating multiple technological advancements and strategic decisions to ensure feasibility and long-term impact. Moreover, it is expected that many of the technological developments needed by the PSS are of interest for other missions and applications, such as space-based solar power or in-space manufacturing for very large space stations. For this reason, an evolution of the roadmap may consider development efforts not uniquely driven by the PSS programme. Such an approach can reduce the overall economic burden by leveraging synergies with other space initiatives.

3.2. Roadmap programme

To achieve initial operations by 2040, it is crucial to begin development as soon as possible, focusing on promising technologies and executing precursor missions that serve as demonstrators of technological maturity and reduce programme risk.

The first precursor mission should aim to demonstrate and validate technologies such as solar sailing and spacecraft operations around the L_1^* point. This is shown in Fig. 3 with the overall programme roadmap beginning with precursor missions in the 2025–2040 timeframe. It will be paramount for these precursor missions to gather data on the orbital environment at L_1^* and study long-term effects on the spacecraft, such as membrane degradation in solar sails. The details of a Planetary Sunshade precursor mission concept are presented in (Coco et al., 2025).

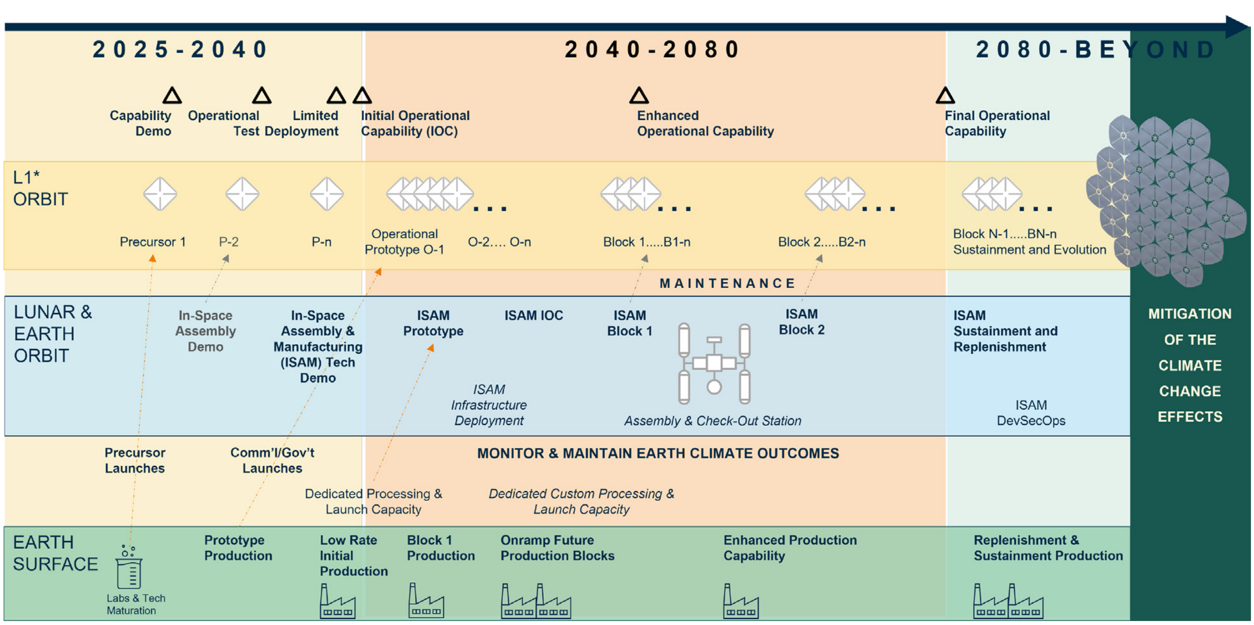

Fig. 3. A preliminary technology roadmap for the Planetary Sunshade programme.

With an estimated budget needed for the precursor mission of the order of tens of US millions, this mission represents a tangible step forward.

Then, a series of progressively more complex precursor missions should be planned, each of which introduces more advanced technologies and operational challenges. Some of these missions can be conducted within the Earth/Moon system, such as in-space automatic assembly and the operation of smaller swarms flying in formation (the activities in the Earth/Moon systems are depicted in the central band of Fig. 3).

One of the central technologies required for the Planetary Sunshade is the development of the membrane that will form the sunshade itself. While existing solar sail membranes are relatively easy to produce and could serve as initial sunshades, they are not optimized for minimizing the overall mass of the structure. Ideally, these membranes should utilize diffraction or interference to redirect sunlight away from Earth, significantly reducing the total mass required (Roger, 2006; Borgue and Hein, 2023; Khodaverdian and Karlsson, 2023). The roadmap in Fig. 3 reflects a focused effort on developing and mass-producing such membranes cost-effectively along with the terrestrial production capacity for all elements of the systems. Until advanced membranes are available, conventional solar sail membranes will be used to support precursor missions and technology demonstrations.

As humanity will likely establish lunar bases in the 2030s and begin to harness lunar resources in the 2040s, manufacturing sunshade components and rocket propellant on the Moon might become feasible and economically advantageous. The roadmap allows for a potential transition from Earth-based to Moon-based manufacturing during the decades-long process of constructing the Planetary Sunshade. Continuous improvements and efficiency gains are expected throughout this period, and the system architecture will be subject to ongoing trades studies and enhancements over its lifecycle.

3.3. Launch and deployment strategies

Space logistics has been improving at a rapid pace, as evidenced by the expectation that the SpaceX Starship will lower launch costs by a factor of 50–100. However, there is no reason to think of Starship as the ultimate exclusive launcher. It is certainly a trailblazer that will show what is possible, but even that can be improved and versions optimal for various purposes will be designed. With millions of tonnes foreseen to be launched for the whole Planetary Sunshade, there should be an optimal launcher designed specifically for this, most likely building upon heritage from Starship and other super heavy launch vechicles currently in development. The roadmap in Fig. 3 reflects this evolution from existing commercial and government launchers supporting the early launches to the possibility of dedicated or customized launchers and processing facilities as the programme matures.

3.3.1. Swarm and on-orbit assembly challenges

In this section it is highlighted the need to analyze the delivery of a swarm of solar sail spacecraft for a PSS, considering the architecture presented in (Matonti et al., 2023). Indeed, to meet the Planetary Sunshade's area requirement of some million km^2, as described in Section 2.2, it will not be possible to build and launch a single enormous sunshade due to the constraints of current launch vehicles. Instead, a large amount of single sunshade units, N, will need to be deployed which could be assembled in space to larger units, or even to one super-large sunshade. To do that, several architectural approaches can be considered.

One possibility is the in-space assembly (ISA) of all solar sail spacecraft, forming a single very large infrastructure (See Fig. 4). In this case, each solar sail unit would adopt a modular spacecraft design with standardized interfaces, enabling an autonomous assembly process relying on robotic systems, potentially including free-flying assembly robots (Zhihui Xue et al., 2021). This approach introduces a range of technological challenges for in-space assembly, particularly in the construction and maintenance of such large space structures, necessitating the development of robust robotic systems, precise control mechanisms, and advanced maintenance strategies to ensure successful deployment and long-term operation. However, significant progress is being made in the field of ISA, with advancements in autonomous robotic technologies, modular design, and on-orbit manufacturing techniques, making such complex undertakings more feasible in the future. Once completed, this architecture eliminates the risk of collision between units that can be relevant in the other architectures. Another option involves a swarm of solar sail spacecraft, which may either be deployed individually or result from a pre-assembled phase. This swarm can operate by maintaining an equilibrium condition to cover the required area or by following closed orbits around the photo gravitational equilibrium point.

The roadmap graphic in Fig. 3 allows for the possibility of In-Space Assembly and Manufacturing (ISAM) as these system trade studies are resolved. Additionally, since L_1^* and the near realms are an unstable, chaotic and perturbed dynamic regime, maintaining an equilibrium condition is challenging, increasing the risk of collisions and reducing the safety. The swarm architecture is more efficient and realistic, particularly by considering periodic or quasi-periodic solar-sail motion around L_1^*. The solar-sails would be distributed along different families of halo orbits, maintained through an active control law which exploits the SRP, without the consumption of propellant (Matonti et al., 2023). These orbits are designed to not intersect each

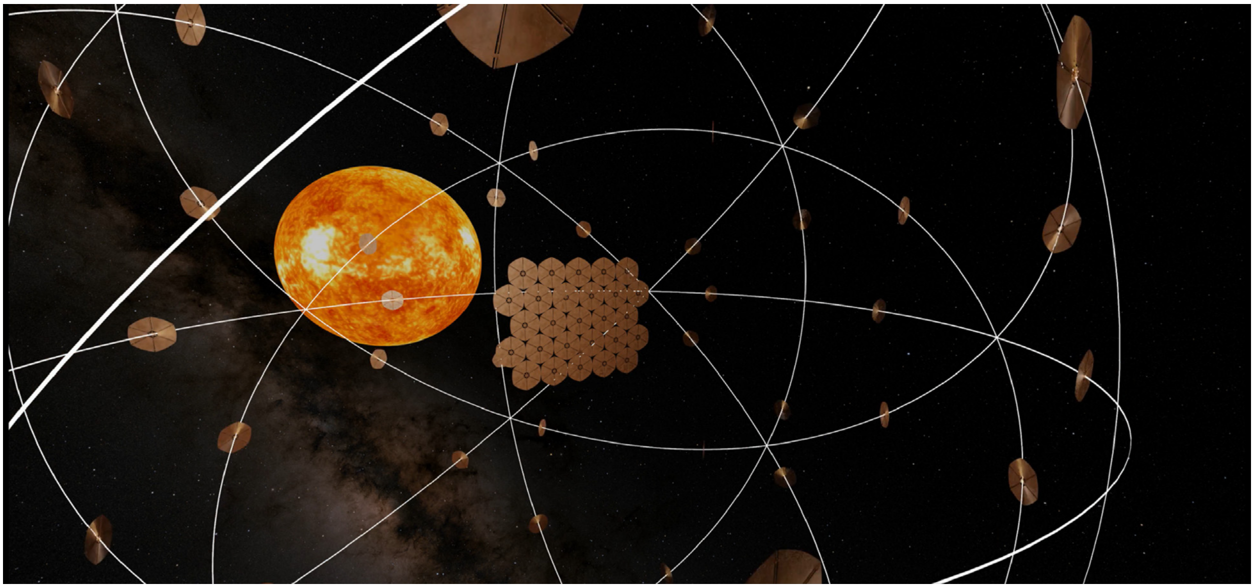

Fig. 4. Conceptual visualization of a Planetary Sunshade System during in-space assembly operations.

other, to avoid possible collisions, and to have minimal variation of the attitude, to maximize the shading. Moreover, active attitude control in motion enhances the system's ability to manage dynamic perturbations, further improving stability and operational safety.

3.3.2. Launchers, launches, and commissioning

It is important to get a rough understanding of the logistic challenge for launching the PSS (Chesley et al., 2023; McInnes, 2010). In this section we show order of magnitudes for one set of assumptions, i.e. by locating the PSS at the optimal L_1^* position to minimize its mass and considering current state of the art technology for the shade size and reflectivity. The launcher capability is based on the expected performance of the reusable Starship-Super Heavy. Many of the output numbers scales linearly with the inputs of Radiance reduction $\Delta = 1.7\%$, reflectivity around $\mathcal{Q} = 0.6$ and lead time to full operation of 40 years as discussed above.

Other key driven factors include the payload capacity, assumed to be approximately 150 tonne. A single launch may indeed carry many of sunshade spacecraft, without considering any volume constraints. Finally, the daily launch rate per launchpad is assumed to be around four launches per day. Each spaceship is expected to be reused approximately 12 times, while boosters and tankers are assumed to have much higher reusability, at around 1000 and 100, respectively. Then, the total mass that must be delivered to space is estimated at 170 million tonne. The PSS structure would need to cover a circular area with a radius of approximately a 1400 km, requiring the deployment in the order of 60 million solar sail spacecraft with an assumed areal density of about 30 g/m^2.

In total, 1 million spaceship launches would be needed, requiring approximately 10 million booster launches and 10 million tanker launches. In terms of production, around least 100 thousand spaceships, 10 thousand boosters and 100 thousand tankers would need to be manufactured over the project's duration, if we consider a transfer with spaceship with refueling in orbit. If indeed the solar sailing strategy is used, several cost for the propellant can be cut. The daily launch rate would have to reach around 800 launches per day, necessitating the operation of at least 200 launch sites worldwide.

3.4. Logistic, programmatic

Manufacturing the millions, or even perhaps a billion, individual spacecraft necessary for the PSS demands highly efficient mass production facilities. However, this scale of production is feasible–Tesla's Fremont factory alone produced 1.8 million cars in 2023 (Kane, 2024). A few specialized sunshade spacecraft factories should be established near launch sites. To maximize economic and technological benefits, both launch facilities and factories should be globally distributed. The development of manufacturing capacity to support the program in parallel with the launch infrastructure is also reflected in the top-level roadmap in Fig. 3.

Additionally, the reusability and the capability of multiple launches per day would significantly constrain the feasibility of the PSS, considering also its critical request for resources and cost.

3.5. Manufacturing and facilities challenges

The manufacturing and deployment of the PSS presents significant challenges due to the scale of production, material requirements, and infrastructure demands (Borgue and Hein, 2023). The roadmap highlights the necessity of large-scale terrestrial manufacturing for thin-film solar sail membranes, the establishment of high-throughput assembly lines, and the need for a global logistics network to sustain a continuous deployment cycle.

A key challenge is the mass production of solar sail membranes and support structures. The roadmap outlines the use of existing solar sail materials for initial deployments, with future iterations shifting towards optimized diffraction-based membranes to enhance shading efficiency while minimizing mass (Thompson et al., 2024). However, producing these materials at a scale necessary for deployment remains a major technological hurdle. Manufacturing processes such as roll-to-roll thin-film deposition (Palavesam et al., 2018) and precision coating techniques (Hołyńska et al., 2018) must be adapted to support high-volume production.

The assembly and integration of these structures require a highly automated production pipeline. Given the complexity of the spacecraft design, modular fabrication approaches will be needed to streamline manufacturing and reduce costs. Co-locating production facilities with launch sites is essential to minimize logistical constraints, ensuring a seamless transition from manufacturing to launch integration. The roadmap suggests a potential long-term shift towards lunar-based production (Labeaga-Martínez et al., 2017), leveraging in situ resource utilization to reduce Earth-based material requirements. However, this transition remains a distant goal, dependent on advancements in space-based manufacturing and robotic assembly.

Another significant constraint is launch cadence and infrastructure capacity. This demands the development of dedicated high-throughput launch facilities, capable of rapid payload integration and turnaround. The roadmap also emphasizes reusability as a key factor in enabling sustained deployment, with booster and tanker production scaled accordingly to support repeated flights.

Finally, sustainability and environmental considerations are critical aspects of the manufacturing roadmap. The production of thin-film solar sails and supporting structures will require substantial industrial capacity, necessitating the adoption of renewable energy sources and waste reduction strategies to mitigate environmental impact.

3.6. Environmental and safety considerations

Despite being one of the less risky geoengineering methods, the potential negative effects of a Planetary Sunshade must be thoroughly investigated. This includes analysing the environmental impact of rocket exhausts, the carbon footprint of manufacturing processes, and the potential creation of NOx in the stratosphere due to reentry of launch vehicles. Additionally, the roadmap should address how best to implement latitude variations in the sunshade (Sánchez and McInnes, 2015).

4. Risks and costs

The development of the PSS entails significant risks and costs, which necessitate careful consideration and planning to ensure the project's success. The primary risks associated with the project include the probability and severity of damages to individual units of the sunshade, as well as the challenges of mitigating these risks without compromising the overall system.

4.1. Damage to sunshade units

The Planetary Sunshade System, being composed of potentially thousands or millions of individual solar-sail spacecraft, is susceptible to damages from micrometeoroid impacts, radiation, and mechanical failures during deployment. In practice, the performance of solar-sail units is constrained by the degradation of their optical and mechanical properties due to prolonged exposure to the harsh space environment. The interaction with ultraviolet radiation, high-energy particles, and micrometeoroids alters the optical properties of the sail surface (Ya. Kezerashvili, 2014), while long-duration exposure may also introduce thermal constraints and progressively modify the effective thrust profile, which must be properly accounted for in mission design (Edwards et al., 2004). These aspects, including the effects of ultraviolet radiation, gamma radiation, the corpuscular component of solar radiation, charging phenomena, and temperature limitations, are discussed in more detail in Coco et al. (2026) where the optical degradation model is refined by incorporating multiple degradation sources based on available experimental data.

Each unit's damage could potentially impair the system's effectiveness, but the design must ensure that such damages do not lead to catastrophic failure of the entire system. This requires the implementation of a robust fault-tolerant system and redundancy in spacecraft deployment and operation.

4.2. Logistical risks

The complex logistics involved in manufacturing, launching, and assembling the sunshade units present significant risks. These include potential delays in production, unexpected failures during launch, and challenges in assembling and coordinating the sunshade in space. The project must account for these risks by developing contingency plans, ensuring flexibility in the project timeline, and securing reliable international partnerships for various stages of the project.

4.3. Technological risks

The technology required for the PSS, such as the solar sails, launch vehicles, and assembly mechanisms, involves cutting-edge developments that may face unforeseen challenges. The current low TRLs of some of these technologies add to the risk profile, emphasizing the need for ongoing research, development, and testing to mitigate technological risks.

A preliminary assessment of Technology Readiness Levels (TRLs) highlights the gap between existing capabilities and those required for full-scale deployment. Conventional solar sail membranes have reached TRL 6–7 through missions such as IKAROS and LightSail (McInnes, 1999; Thompson et al., 2024). However, advanced membranes leveraging diffraction or interference, that could reduce mass by orders of magnitude compared to conventional reflective membranes, remain at TRL 2–3, requiring fundamental research and laboratory validation (Roger, 2006; Borgue and Hein, 2023; Khodaverdian and Karlsson, 2023).

Robotic assembly of large structures in orbit is at TRL 4–5, demonstrated by ISS servicing and DARPA OSAM initiatives (Chesley et al., 2023), while fully autonomous assembly of system as ultra-thin membranes at Lagrange points is at TRL 2–3, with demonstration that will need to cope also with large-scale assembly challenges.

Solar sailing is at TRL 6, validated in interplanetary missions (McInnes, 1999), whereas high-power electric propulsion for large-scale transfers is at TRL 5–6, but scaling to millions of units demands significant maturation (Matonti et al., 2023; Oggionni et al., 2022).

Formation flying for small constellations is at TRL 5–6 (e.g., ESA Proba-3), but swarm control for thousands to millions of units in chaotic Lagrange environments is at TRL 2–3, requiring new algorithms and hardware (Matonti et al., 2023; Matonti and Romano, 2024).

This TRL analysis underscores the need for a phased roadmap with precursor missions to raise technology maturity before committing to full-scale deployment.

4.4. Institutional and political continuity risk

Beyond technical and logistical considerations, another relevant risk factor concerns the long-term institutional and political continuity required to sustain a very large space infrastructure. The development and operation of a Planetary Sunshade System would likely span several decades, requiring sustained financial commitment, international coordination, and programmatic stability. Changes in political leadership or shifts in policy priorities may affect the level of political will and funding allocated to the project over time. For this reason, ensuring stable governance structures and long-term international agreements would be essential to guarantee the continuity of the program throughout its operational lifetime.

4.5. Manufacturing costs

The production of millions of sunshade spacecraft represents a significant cost driver. This includes not only the material costs but also the costs associated with developing new manufacturing facilities, workforce training, and quality assurance processes. The choice of materials, such as lightweight reflective coatings and durable membranes, will heavily influence the overall costs.

It is not easy to estimate the cost of a fairly unknown unit, but one can try to argue along the line of (Fuglesang and de Herreros Miciano, 2021), that the cost of a mass produced product which is not particularly complicated roughly scales with mass. One can then compare with cars, which have prices in the order of 10 USD/kg. With a total mass for the whole system of 100 million tonne, assumed to be built up by very many identical small units, the total manufacturing cost would be 1 trillion US dollar. Note that car prices include the cost of development and the same can be assumed for sunshade spacecraft.

4.6. Launch costs

Launching the sunshade units into space is another major cost factor, in terms of units production, propellant and launch and production sites. With advancements in space launch technology, such as the development of SpaceX's Starship-Superheavy, the cost per kilogram to space is expected to decrease. However, the sheer volume of material to be launched means that total launch costs will still be substantial. The need for multiple launch sites and the coordination of frequent launches add to these expenses.

There are hopes that the price per kilogram launched to LEO could get as low as 10 USD in the future, even with Starship (Wang, 2024). Here, a more conservative approach is taken, assuming a price by 2040 of 50 USD/kg. The total launch cost for 100 million tonne would then be 5 trillion USD.

If this is added to the manufacturing cost above, the overall cost would be 6 trillion USD. Over 30 years, this is 200 billion USD per year, which can be compared with the current global GDP of about 100 trillion USD.

4.7. Operational costs

Once deployed, the sunshade system will require ongoing operations and maintenance, including station-keeping, monitoring, and potential repairs or replacements of damaged units. The costs associated with these operations must be included in the overall budget, along with provisions for unforeseen operational challenges.

5. The policy context

European Union (EU) has taken a leadership role in climate change mitigation, encapsulated in the European Green Deal. This ambitious initiative aims for the EU to become climate neutral by 2050, with a significant milestone of a 55 % reduction in greenhouse gas emissions by 2030, relative to 1990 levels (European Environment

Agency, 2025b). The European Climate Law enshrines these targets, demonstrating the EU's commitment to sustainable development and the deployment of green technologies. To achieve these goals, the EU has implemented policies promoting renewable energy, enhancing energy efficiency, and fostering green job creation. The European Environment Agency (EEA) provides detailed monitoring and reporting on the progress of these initiatives, maintaining a comprehensive database of national policies and measures adopted by member states.

On a global scale, effective climate change mitigation necessitates coordinated international efforts. The International Monetary Fund (IMF) emphasizes the critical role of international cooperation in climate policy, facilitating frameworks that allow for the comparison and alignment of climate mitigation strategies across different nations (Black et al., 2022). Global agreements such as the United Nations Framework Convention on Climate Change (UNFCCC), the Intergovernmental Panel on Climate Change (IPCC) and the Paris Agreement underscore the importance of collaborative efforts to reduce greenhouse gas emissions. These international frameworks support innovative solutions like PSS, which proposes the deployment of a solar light umbrella in space to regulate the solar radiation reaching Earth and mitigate global warming.

Integrating space-based climate mitigation strategies into existing policy frameworks poses significant technological, logistical, and cooperative challenges. The development of a PSS necessitates advancements in space engineering, robust international collaboration, and thorough environmental assessments. The supportive context provided by European and global policies facilitates the exploration and potential implementation of such advanced technologies (European Environment Agency, 2025a; Black et al., 2022).

5.1. International collaboration and coordination

The scale of the Planetary Sunshade project necessitates international collaboration, which introduces additional costs related to coordination, regulatory compliance, and the establishment of international agreements. These costs, while not directly linked to the physical construction or deployment of the sunshade, are crucial for the project's success and sustainability.

5.2. Political challenges

The implementation of the Planetary Sunshade System, a space-based geoengineering solution designed to mitigate the effects of climate change, faces significant political challenges. These challenges are shaped by the system's global nature, technological complexity, and the far-reaching consequences of climate intervention. Successfully navigating these obstacles will be essential for the project's success and legitimacy on the world stage. One of the most critical political challenges surrounding the Planetary Sunshade System is the urgent need for an internationally agreed-upon governance framework. The system would have a global impact by reducing solar radiation and altering climate patterns across the Earth. This global governance is not just a preference, but a necessity for the successful and ethical deployment of the system.

5.3. International regulations

Establishing international regulations and agreements is crucial for ensuring that the use of this system is fair, transparent, and driven by the collective interests of all nations. The United Nations or a similar global body may need to take the lead in creating treaties or protocols to govern the Planetary Sunshade's development, deployment, and operation. This framework would need to address issues such as:

- Which nations or international organizations can decide when and how to deploy the sunshade system?
- How will the system be managed, monitored, and maintained to ensure it operates within agreed-upon parameters?
- If the system has unintended negative consequences, who will be held accountable, and how will affected nations or populations be compensated?

These questions will require careful negotiation to balance the interests of different countries, especially between developed and developing nations. The potential for conflicts over control and influence in the decision-making process could be high, as powerful nations with advanced space programs may attempt to dominate discussions.

5.4. Ethical implications

The ethical implications of deploying a planetary-scale geoengineering system are profound. Altering the Earth's climate, even with the intention of mitigating the catastrophic effects of global warming, involves significant moral responsibility.

5.5. Equity and fairness

The uneven distribution of climate change impacts introduces complex political challenges in deploying a global geoengineering solution like the PSS. While developing nations, particularly in the Global South, face disproportionate risks due to climate change, the technological and financial capabilities to implement such systems are largely concentrated in wealthier nations. This creates potential for inequitable decision-making, where the voices of the most vulnerable may be marginalized in international agreements. Moreover, the benefits of climate intervention may not be uniformly distributed, with some regions possibly experiencing unintended consequences, such as altered weather patterns or agricultural disruptions. To address these disparities, the governance structure for the PSS must ensure inclusive representation from all affected nations, especially those most vulnerable, and include mechanisms for compensation and adaptation support to mitigate any negative effects. This approach is critical for fostering a fair and just global response to climate change through geoengineering.

5.6. Public perception and acceptance

Public acceptance and trust in the PSS are critical for its deployment and long-term success. However, public perception of geoengineering technologies is often marked by skepticism due to concerns over potential risks and unintended consequences. Many environmental organizations advocate for conventional climate mitigation strategies such as reducing greenhouse gas emissions through renewable energy adoption and conservation efforts. These groups may oppose geoengineering initiatives, including the Planetary Sunshade, on the grounds that it could act as a temporary solution while allowing the continuation of unsustainable practices, thus failing to address the root causes of climate change, a concept referred to as the "moral hazard" of geoengineering. Additionally, large-scale interventions in natural systems may evoke public distrust, with fears centered on the ecological and societal consequences. Without transparency and a well-communicated risk management framework, the legitimacy of the PSS project could be undermined, potentially facing opposition from civil society, political entities, and governments. To build public trust and political legitimacy, it will be essential to engage in broad, multi-level stakeholder consultations, emphasizing the system's scientific basis, benefits, and safeguards. Public outreach and education efforts, coupled with transparent governance, will be necessary to position the system as a viable, responsible tool within a comprehensive climate mitigation strategy.

5.7. Moral hazard and the risk of slowing climate mitigation efforts

A major concern with geoengineering solutions like the Planetary Sunshade is the potential for "moral hazard", where the availability of technological fixes could reduce the urgency for sustainable practices. If perceived as a substitute for emissions reduction, this could undermine efforts to transition to renewable energy and weaken global climate commitments, such as the Paris Agreement. The risk lies in geoengineering being viewed as a quick fix, leading to complacency in addressing the root causes of climate change, such as fossil fuel dependency. To mitigate this, policymakers and scientists must emphasize that the Planetary Sunshade is a complementary measure, not a replacement, and should be integrated alongside traditional mitigation strategies like emissions reduction and energy efficiency. This ensures geoengineering is part of a holistic approach to climate action.

6. Conclusions

This paper presents a roadmap for a space-based solar geoengineering programme aimed at reversible Solar Radiation Management to mitigate global warming through a Planetary Sunshade System. The roadmap addresses the main elements required for full development, including the enabling technologies, launch architectures, and swarm logistics at the photo-gravitational L_1^* point. The Planetary Sunshade System demands substantial advances in the state of the art of manufacturing, assembling, and deploying ultra-thin membrane structures, as well as in managing large-scale space logistics for a very large number of units.

A key outcome of this work is that the overall feasibility of the Planetary Sunshade roadmap is critically dependent on progress in solar sail technology. Indeed, solar sails are not merely one subsystem among many. They are the enabling mechanism for both propulsion and attitude control of individual shade units, and thus for the global architecture of the system. The optical performance (e.g., reflectivity, diffraction efficiency), mass efficiency, and controllability of solar sails directly determine the total mass, number of units, transfer strategies, station-keeping requirements, and therefore the Planetary Sunshade scalability, cost-effectiveness, and operational robustness. In particular, the achievable areal density and controllable optical properties of the membranes set the magnitude of the launch and manufacturing effort, while the precision of attitude and formation control drives the reliability of shading performance and collision avoidance in the vicinity of L_1^*.

For these reasons, targeted research and demonstration missions in solar sail technology emerge as essential near-term priorities within the roadmap. These include: (i) the development and testing of advanced membrane materials and coatings optimized for mass efficiency and tailored optical response; (ii) in-orbit demonstrations of deployment dynamics for large, ultra-thin sails; and (iii) autonomous attitude and formation control exploiting Solar Radiation Pressure for both station-keeping and coordinated swarm behaviour. The precursor missions envisaged in the roadmap should therefore be explicitly designed to raise the Technology Readiness Level of these key solar sail capabilities, as well as to characterise long-term degradation phenomena in the L_1^* environment.

Building on this technological foundation, the roadmap phases are outlined in chronological order, highlighting the critical and operative factors during the deployment of the Planetary Sunshade Programme. We suggest a gradual approach starting with a set of precursor missions over the next two decades, followed by an initial operational phase by 2040 and full deployment by 2080. The large-scale production of the modules and their deployment into orbit will require dedicated industrial and transportation infrastructure, leveraging economies of scale and benefiting from parallel developments in other areas such as in-space assembly and space-based manufacturing.

In parallel, political, legal, and ethical challenges must be addressed, including the definition of appropriate international governance frameworks, mechanisms for equity and accountability, and processes for meaningful public engagement and acceptance. The magnitude and global impact of a Planetary Sunshade make international cooperation indispensable, both to ensure fair decision-making and to manage potential regional side effects.

Ultimately, the Planetary Sunshade System represents a potentially effective and reversible strategy for climate change mitigation, provided that its technological, environmental, and governance challenges are rigorously addressed. The proposed roadmap serves as an initial framework for designing and developing such a system and for structuring the research agenda, especially in solar sail technology, needed to assess its viability. Crucially, the Planetary Sunshade System should not be seen as a substitute for greenhouse gas emission reductions, but as an analytical and programmatic tool to explore whether, and under which conditions, direct climate intervention from space could play a complementary role within a broader portfolio of mitigation and adaptation measures.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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